EFFECTS OF ABNORMAL CONDITIONS ON ACCURACY OF ORIFICE MEASUREMENT

Class # 1100

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Introduction

In 1971 E. J. Burgin of Florida Gas Transmission Company presented a paper at ISHM entitled “Factors Affecting Accuracy of Orifice Measurement (Primary Element)”. Burgin noted that AGA Report No. 3 (of that time) claimed that an orifice meter with flange taps and with a diameter ratio, β, between 0.15 and 0.7, fabricated and operated in accordance with the specifications in the standard, would have a discharge coefficient value within ± 0.5% of the value calculated from the orifice equation. The purpose of Burgin’s paper was to examine some of the specifications in the orifice meter standard and to review the effect upon measurement accuracy when the specifications are ignored.

Burgin reviewed data from tests sponsored by the AGA Gas Measurement Committee during the period 1925-1930 as well as additional field-test data taken at Florida Gas Transmission Company. Kemp summarized several of the most significant orifice measurement errors on one page. Every entry on Kemp’s list is an under-measurement error. That is, the actual gas flow rate exceeds the indicated flow rate. The magnitudes of the under-measurement errors ran from less than 1% to from 10% to 25%. There is a large financial incentive to avoid the kinds of abnormal conditions that produce errors of this magnitude.

Since 1971, a wealth of new information on orifice meter measurement accuracy has been published. Botros, Studzinski and Barg with NOVA in Canada published a summary of their investigations of abnormal effects on orifice meter accuracy. Ting with Chevron Petroleum Technology Center also published a paper on the effects of nonstandard operating conditions on orifice meter accuracy. Spencer, Hobbs and Humphreys performed research at the U.K. National Engineering Laboratory (N.E.L.) on errors caused by wear (dulling) or impact damage to the sharp edge of the orifice plate. Tests have been performed in the Gas Research Institute (GRI) Metering Research Facility (MRF) on backwards facing orifice plates and orifice edge sharpness. Other information sources pertinent to the effects of abnormal conditions are listed in the references.

This is a good time to look back over the last 35 years and to compare some of Burgin’s results with the data from the 1970’s, 80’s and 90’s.

Orifice Plate Installed Backwards

Burgin did not discuss the effect of installing an orifice plate with the bevel facing in the upstream direction. It is known that installing a beveled orifice plate backward in an orifice fitting or orifice flange can cause the orifice meter to under-measure the flow rate by from 8% to 25%. Figure 1 shows data for backward facing orifice plates reported by Ting for 4-inch and 6-inch meters and by Witte for a 10-inch meter tube in the MRF. Some 2-inch and 4-inch data from the MRF is also shown. Note that the under-measurement error is reasonably well correlated by the orifice β ratio.

Orifice Plate Edge Sharpness

Assume now that the orifice plate is installed properly, with the sharp, straight edge facing upstream. If the sharp edge becomes rounded, the orifice discharge coefficient may increase and the orifice meter will significantly under-measure the flow rate. Precise measurement of the edge “radius” is difficult. The edge radius can be measured directly by tracing a profilometer stylus from the orifice bore onto the front face of the orifice plate. However, the stylus tip radius is often larger than the edge radius, leading to high measurement uncertainty. The lead foil technique described by Crockett and Upp is simple to use. It involves making an impression of the sharp edge on a soft lead disk, then viewing the impression under high magnification and comparing the magnified image to radius gauges of different sizes to estimate the edge radius.

Burgin presented results for the per cent flow measurement error from tests sponsored by the Gas Measurement Committee during the period from 1925 to 1930. The tests were carried out in air, in 4-inch meter tubes, for three different orifice β ratios. The results are shown in Figure 2 for measurement error as a function of the ratio of the edge radius to the orifice bore diameter. Burgin recommended that the ratio of edge radius to bore diameter not exceed 5*10^{-4} if the error should be limited to 0.2% to 0.3%.

Spencer reviewed data on the effect of edge sharpness on orifice C_d and recommended an empirical correlation shown as the straight line in Figure 2. Spencer suggested that the ratio of edge radius to bore diameter should not exceed 4*10^{-4} if the effect on C_d is to be limited to less than 0.2%.

Edge sharpness measurements using the lead foil method were made on over 100 2-inch and 3-inch diameter orifice plates for the GRI MRF orifice meter installation effects program. The results of the tests are shown in Figure 3 as orifice plate edge radius versus orifice plate bore diameter.

The plates were donated by several companies from their field stocks and were not fabricated specially for the research program. API loaned the 2-inch and 3-inch orifice plates that had been used in the orifice coefficient tests performed by NIST and reported by Whetstone et al.

Spencer's correlation for the maximum allowable edge radius as a function of bore diameter is shown as a straight line in Figure 3.

We can conclude (1) the orifice edge radius may vary from plate to plate; (2) the edge radius is not a strong function of bore diameter; (3) the edge radii of the API orifice plates are not significantly smaller (sharper) than values measured for randomly selected orifice plates; (4) in general, 2-inch and 3-inch orifice plates meet Spencer's criterion for the maximum allowable edge radius for orifice bore diameters greater than 0.375-inch.

Notches or Grooves on the Sharp Edge

Orifice plates are sometimes replaced if visual inspection shows that damage has occurred to the sharp edge and bore region. Burgin cited test results with "nicked" plates in 4-inch diameter orifice meter tubes. Plates with nicks in the sharp edge ranging in depth from 0.020-inches (0.5mm) to 0.050-inches (1.3mm) gave measurement errors ranging from +1% to –0.6% for flange taps.

Hobbs and Humphreys calibrated two orifice plates (β = 0.34 and β = 0.75) before and after localized damage was inflicted to the upstream edge. A cold chisel was held at an angle of 45° against the sharp edge and struck with a hammer. They noted that the metal was not simply removed, but also displaced, and small raised areas were formed around the site of the indentation. After one strike, the plates were recalibrated and measurement errors in the range of –0.02% to -0.18% were found. Further tests made after the notches were deepened gave errors in the range of +0.10% to +0.51%.

An extensive investigation of the effect of artificial damage to orifice plates was reported by Botros et al. A distinction is made between (1) a V-notch which extends clear through the orifice bore (increasing the open area for flow), (2) a V-groove that nicks the upstream face of the plate and the sharp edge, but does not increase the bore area, and (3) a V-bump of plastically deformed material that may extend into the bore of the orifice plate.

Figure 4 shows the results of 4-inch, 8-inch and 10-inch diameter tests for β = 0.20 and β = 0.60 for orifice plates with V-notches machined through the plate. The tests showed that the measurement error was proportional to the relative change of the orifice bore area and independent of β-ratio. Approximately 75% of the error correlated directly to the increase in the bore area. An extra 25% was attributed to an increase in orifice coefficient caused by the local change in orifice shape. Rotation of the V-notch with respect to the pressure taps did not affect the measurement error.

A V-groove that doesn't extend completely through the orifice bore can also cause an error in measurement. Botros et al report results from tests in which a V-groove was machined to different depths on the sharp edge. (Note 1 mm = 0.039-inch.)

• V-notch, 6mm x 6mm	-1.4%
• V-groove, 6mm x 6mm x 1.5mm	-0.6%
• V-groove, 6mm x 6mm x 1.0mm	-0.2%

The error produced by a V-groove depends upon the depth of penetration. The error produced by a V-notch (that extends completely through the bore) was more than double the amount produced by a V-groove. Botros et al suggested that a conservative allowance for the error caused by a V-notch or V-groove is

$$\varepsilon = -8A_n / \pi d^2$$

where A_n is the nick area. The error allowance given by this equation for V-notches and V-grooves is shown in Figure 4. To assure a measurement error of less than –0.05%, the total area of nicks, A_n, should be less than $2*10^{-4} * d^2$. Botros et al state that a **typical small nick** encountered in a pipeline system caused measurement errors in the range of **-0.002%**.

Bent or Warped Orifice Plate

An orifice plate placed between orifice flanges or in an orifice fitting is required to be flat and perpendicular to the direction of flow. Excessive differential pressure across the orifice plate may cause the plate to bend in response to the force applied. For small deflections, the effect of plate bending may reduce the plate bore causing an over-measurement error. However, for large deflections, the orifice bore is increased significantly and under-measurement of flow rate is the result.

Burgin reported results of tests on the effects of plate deflection. For a 4-inch orifice meter, orifice plate deflections of 1/8-inch (either concave in the flow direction, or opposite to the flow direction) gave an under-measurement error of between –2.4% to –3.1%. Surprisingly, for orifice plate deflections of ¼-inch, Burgin cites an over-measurement error of from 8.3% to 9.9%. The change of sign may be a typographical error since an under-measurement error of this magnitude is more likely. Kemp reported measurement errors of from –6.1% to –9.1% for plates warped by ¼-inch and cites Burgin as the source of his information.

Jepson and Chipchase published a comprehensive paper on the effect of orifice plate buckling on orifice meter accuracy. They developed a theory to calculate the flow measurement error from the elastic and/or plastic deformation of buckled (bent) plates. The measured errors for bent plates agreed well with values calculated from their theory. They concluded that plastic buckling of the plate in the flow direction will not cause *over-measurement* of the flow rate by more than 0.5%. However, permanent deformation that causes the plate to deflect by more than about 1° from the true position can result in an *under-measurement* of several percent.

Mason, Wilson and Birkhead developed a theory to predict the flow measurement error for elastic deformation of the orifice plate. These authors showed that the percent error in flow measurement is a function only of the orifice β ratio and the angle of deflection of the orifice plate.

Ting showed experimental results obtained with 4-inch and 6-inch orifice plates that were bent by a press up to 10° in the flow direction. Figure 5 shows the measurement error for a 4-inch diameter $\beta = 0.50$ plate as a function of the orifice plate deflection angle. The measured values are compared with predictions from the elastic deformation model developed by Mason et al. While the trends are similar, Mason's theory over-predicts the magnitude of the measurement error for a given deflection angle. It is also possible that the deflection angle may vary across the face of the plate from the circumference to the bore.

Rough Orifice Plate

To simulate a deep score on the upstream face of an orifice plate, Hobbs and Humphreys machined a 2-mm wide and 1-mm deep V-shaped groove in the radial direction from the sharp edge to the orifice plate seal. No significant change was found when the plate was recalibrated. The effect of scores and scratches on the downstream face was investigated by gluing coarse sandpaper onto the plate. Again, no significant change in orifice discharge coefficient was found.

Botros et al reported different findings. They machined minute concentric grooves with roughness values of R_a = 2 μm (80 μinch) and 4μm (160 μinch) on the upstream and downstream orifice plate faces. Calibrations were performed for $\beta = 0.20$ and $\beta = 0.60$ in 4-inch (100mm) and 8-inch (200mm) pipe sizes. A standard orifice plate with surface roughness of 1.3 μm (50 μinch) was used for comparison.

The results are shown in Tables 1 and 2. Measurement errors exceeding –0.25% are significant.

D = 4-inch	$\beta = 0.20$	$\beta = 0.60$
80 μinch	-0.06%	-0.05%
160 μinch	-0.27%	-0.64%

Table 1. Flow measurement error in 4-inch diameter meter tube caused by orifice plate roughness exceeding 50 μinches.

Only the measurement error for $\beta = 0.60$ and $R_a = 160$ μinch would be considered a significant departure from the 4-inch baseline results.

D = 8-inch	$\beta = 0.20$	$\beta = 0.60$
80 μinch	-0.57%	-0.19%
160 μinch	-0.70%	-0.47%

Table 2. Flow measurement error in 8-inch diameter meter tube caused by orifice plate roughness exceeding 50 μinches.

The error magnitudes for the 4-inch and 8-inch diameter plates for $\beta = 0.60$ are consistent. However, the 4-inch and 8-inch results for the $\beta = 0.20$ plates vary by about 0.5%. The results show that a $\beta = 0.20$ plate with $R_a = 80$ μinch caused an under-measurement error nearly 0.5% larger than a plate with $R_a = 50$ μinch. More research would be useful to confirm these results. Still, increasing plate roughness over the face of the orifice plate from 50 μinch to 160 μinch accounts for an under-measurement error of less than 1%.

Grease Deposits on the Orifice Plate

Botros et al note that the valve maintenance in meter stations may sometimes produce valve grease spots deposited on the orifice plate. Tests were performed for $\beta = 0.20$ and $\beta = 0.60$ in an 8-inch meter tube to estimate the severity of the problem using eight circular disks about 1/16th inch (1.7 mm) thick by about 3/8th inch (10 mm) in diameter. The eight disks were attached either up against the sharp edge or midway up the front face from the pipe wall to the orifice bore. No significant effect on measurement accuracy was found when the disks were placed midway between the pipe wall and the orifice bore. When the disks were adjacent to the orifice bore, significant measurement errors of –1.0% for $\beta = 0.60$ and –3.25% for $\beta = 0.20$ were found.

The Florida Gas Transmission Co. tests reported by Burgin included as variables the thickness of the deposit on the plate and the area of the plate covered by grease. Three "gob-type" random deposits on the upstream side of the plate caused no error, while nine random deposits produced an error of –0.6%. Coating the bottom 50% of the plate with a 1/16th-inch thick layer of grease gave a –9.7% error. Increasing the coverage area to 100% increased the error to –15.8%. Increasing the thickness of the grease coating to 1/8th-inch and coating the bottom half of the plate (front and back) gave an error of –10.1%. Coating the full face of the plate (front and back) gave an error of –17.9%. Increasing the grease thickness to ¼-inch and coating the full face of the plate (front and back) gave a measurement error of – 24.4%.

Liquid Film on the Orifice Plate and in the Meter Tube

Johansen of CEESI investigated the effect of a thin coating of compressor lubrication oil liquid on orifice flow meter surfaces. Tests were performed on 2-inch, 6-inch and 10-inch meter systems for three different values of β. Baseline calibrations were performed first with dry plates and meter tubes. Next, the orifice plates were dipped in oil. Excess oil was allowed to run off, and the plates were reinstalled in the meter tubes. Following these calibrations, the meter tubes were coated with oil, excess oil was drained off, and the calibrations were repeated again. The results were calculated as the change in orifice discharge coefficient, C_d, caused by the oil film. An increase in discharge coefficient causes an under-measurement of the flow rate (a negative metering error).

Figure 6 shows one set of test results for the 6-inch meter tube and $\beta = 0.67$. Baseline C_d values have been subtracted from the wet plate and wet plate and wet meter tube results, and the results plotted as metering error versus pipe Reynolds number.

The figure shows that the effect of the oil film on the orifice plate was less than 0.25% and was not significant. Johansen observed that either oil on the plate did not contribute to a metering error, or the gas flow stream and radial pressure gradient swept the oil away from the plate face.

Figure 6 shows that oil in the upstream section of the meter tube produced a significant measurement error. The magnitude of the error decreased with time, probably as oil was swept away from the meter tube surface. Johansen observed that the error could be due to a flow of oil from the tube to the plate, or simply due to the effect of oil in modifying the surface roughness of the meter tube. Waviness of an oil coating on the inside of a pipe effectively increases the surface roughness of the pipe. Increasing the pipe wall surface roughness is known to affect orifice coefficient for high β values. This would explain why the effect of oil in the meter tube was significant for $\beta = 0.67$, but not for $\beta = 0.37$ or $\beta = 0.21$.

Conclusions

Meter tubes and orifice plates are inspected by the manufacturer to assure that they are in compliance with AGA Report No. 3 specifications. Proper maintenance and routine inspections can provide assurance that an orifice metering facility continues to comply with the AGA Report No. 3 specifications.

Significant errors may occur if the sharp edge becomes dull, or if the plate becomes dished (bent) due to overpressure damage. Localized (isolated) damage to the sharp edge and bore may not be significant unless it extends completely through the plate thickness. Minute grooves and/or scratches on the plate surface that do not enlarge the bore area may not require replacing the orifice plate. A notch that does enlarge the bore area justifies discarding that plate.

Accumulations of grease, oil, dust and dirt on the orifice plate can cause significant errors. The severity of the effect apparently depends upon the coverage area and the thickness of the deposits. Accumulation of liquid in the upstream meter tube segments may also produce measurement errors if it increases the effective roughness of the meter tube surface.

The effects of abnormal conditions have been discussed as if they occur separately. Yet, in field measurements it is quite possible that several different effects will be combined. Little is known about combinations of effects, particularly those that may act to augment or offset one another. The best strategy is to inspect and maintain the orifice plate and meter tube in the same condition as it was delivered from the manufacturer.

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Figures

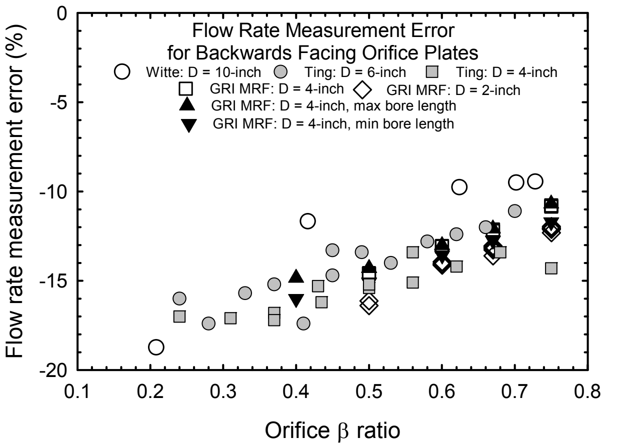

Fig. 1 Measurement error caused by installing orifice plate backward in orifice fitting or flange.

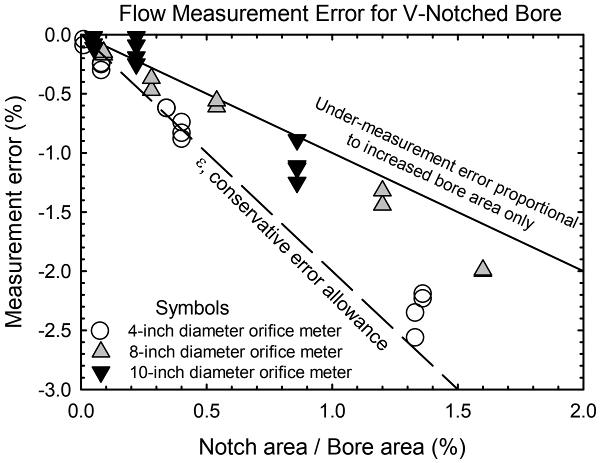

Fig. 4 Flow measurement error for orifice plates with V-notchs machined into the sharp edge.

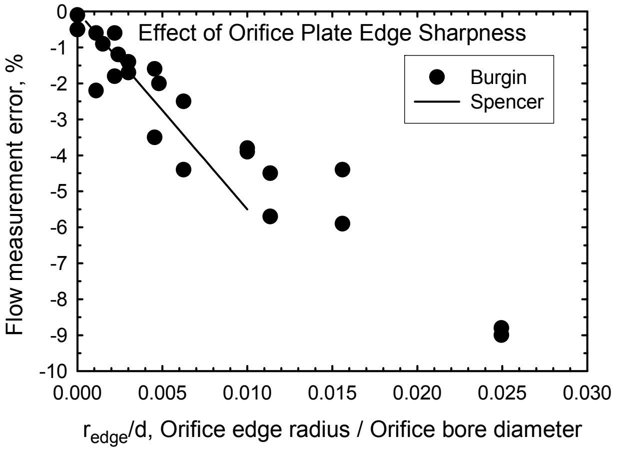

Fig. 2 Measurement error caused by rounding the sharp orifice plate edge.

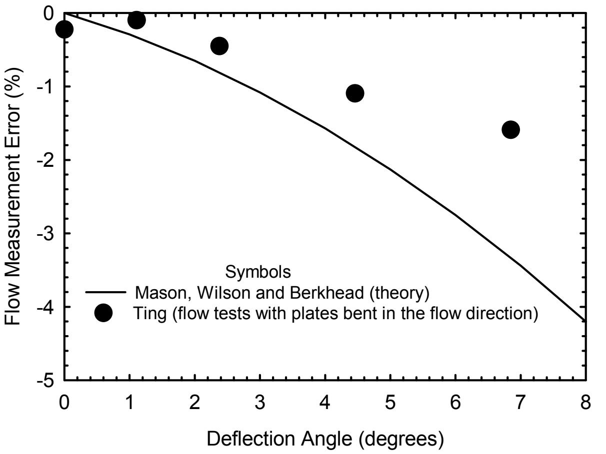

Fig. 5 Measurement error for 4-inch diameter bent plate with β = 0.50

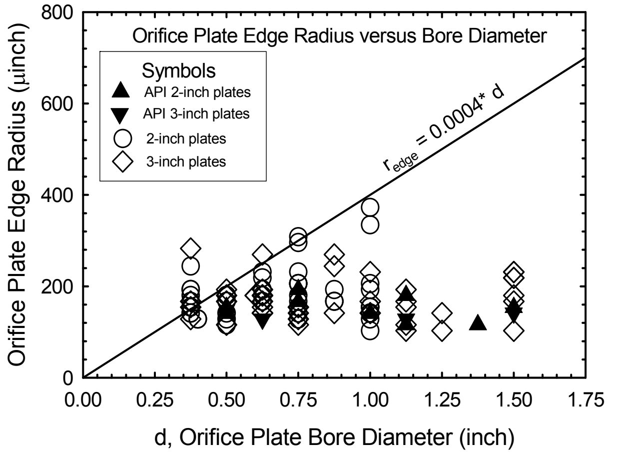

Fig. 3 Measured values of sharp edge radius for 2-inch and 3-inch orifice plates.

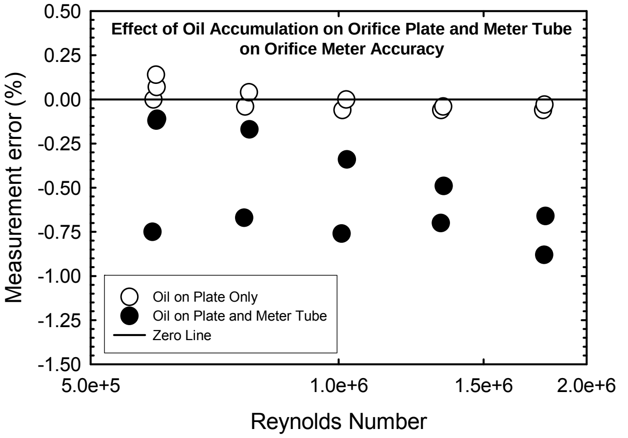

Fig 6 Effect of oil film on orifice plate and on orifice plate and meter tube.